Abstract

Simulation of the large scale test performed at the RCW facility in the frames of MASCA required development of a special model which include different phenomena such as natural circulation in the molten pool, electromagnetic heating, corium melting and refreezing. Additional model describing diffusion of corium components was also implemented. Results of numerical analysis and interpretation of experimental results is presented in the paper. Presented model predicts reasonably main phases of the test such as initial heating, and spreading of molten area. Behaviour of the metal layer after steel addition was described using diffusion model for uranium and zirconium component.
Introduction

The behaviour of the core components (U, Zr, O, Fe(SS) and fission product (FP) simulants under prototypic conditions were studied in the frames of MASCA Project in a series of small scale tests STFMFe [1], STFMFP [2], and medium-scale tests MA [3, 4 and 5]. In the course of these tests, the effect of uranium and zirconium extraction by molten steel during interactions with the suboxidised corium melt was revealed and studied. This effect impacts significantly the compositions, densities, and properties of coexisting molten phases and the structure of the melt stratified pool. It was found that during interaction molten steel relocates to the bottom of the crucible due to increase of metal phase density.

The cold crucible is the basic element of the RCW facility design. Figure 1 demonstrates the facility schematics. The facility consists of two sections located vertically one above the other and integrated into one assembly. Corium briquettes and FP simulants are heated inductively in the lower section up to its melting temperature (2500 – 2600°C). Necessary thermal resistance from the cold walls insulation was provided by the layer of UO$_2$ and C-100 corium 8 mm thick. After melting process was completed, steel preform is melted in the upper section, and molten steel relocates down through the discharge channel onto the corium melt in the lower section.

The height of the melting compartment in the lower section is 700 mm, the inner diameter is 176 mm.

A pipe of the start-up tungsten heater 65 mm long located along the compartment axis was put into the loading down to the depth ~ 100 mm. Tungsten heater was heated by the inductor field with the frequency 8 – 10 kHz up to the temperature of 2500 – 2600 °C. In turn, the surrounding briquettes were heated from the tungsten tube by conduction and up to the formation of electrically closed rings and high enough temperature to reach sufficient value of electric conductivity in loaded corium (at f = 10 kHz, $T_{\text{initial heat generation}} \approx 2000$ °C, close to sintering temperature).

After that, the corium intercepts the absorbed power of the electromagnetic field and corium is heated volumetrically to its melting temperature of about 2350 – 2450°C. At this moment, tungsten heater is retracted from the facility (tungsten is incompatible with the molten steel component).

Propagation of the corium melting front from the centre to the periphery and then downwards through the loading with the increase of the high-frequency inductor power absorbed by the corium was controlled by the set of peripheral thermocouples. The process of melting, as a whole, was quite stable due to the autoacquisition in the balance of power absorbed and removed from the corium to cooling water. That is, with the increase of power deposition in the corium, the temperature rise leads to the change in the properties and reduction in the thickness of the thermal insulation loading layer that in turn results in the increase of the thermal flux and thermal losses through the wall. Thus, powers of heat generation and thermal losses are equalized. The same processes but of the opposite character takes place with the reduction of the input power.

A melting compartment of the upper section is formed by a tungsten pipe-heater insulated from the cold crucible pipes by the layers of Al$_2$O$_3$ coating (the layer is 10 mm thick) and of ZrO$_2$ powder (the layer is 14 mm thick). The compartment is supported by heat-insulating rings made from ZrO$_2$ ceramics. Inside the compartment, a stainless steel charge (a pipe ~ 9 mm thick) is placed into the case made from ZrO$_2$ ceramics. The case prevents the contact of melting steel with the heater tungsten. At the desired moment (after the production of the melt pool in the lower section), the tungsten heater is heated up to the temperature 2200 – 2400°C by switching on the upper inductor (the frequency of electric power supply is 2.4 kHz). Energy from the tungsten heater transferred by radiation, first to ZrO$_2$ case and from that – to the stainless steel preform that was melted and released down through the discharge channel made of ZrO$_2$ ceramics.

The facility was equipped with the thermocouples for the monitoring of heating – melting processes and for the technological control. Detailed description of instrumentation is presented in the report [6]. In Figure 1 location of thermocouples which data will be compared with the results of analysis are shown.
Before the test run pretest analysis was performed which allowed to specify main phases such as

1. Heat up at the moderate level of power up to the target tungsten temperature of about 2200°C;
2. Removal of the starter heater from the crucible after the melt front reached cold walls;
3. Sustained heating of corium at the appropriate power level to provide the corium heating and melting;
4. Heating of steel in the upper section and pouring of that into the melted corium;
5. Quasi-steady state operation.

It was expected that heating power would move into the corium at the temperatures about 2200°C. The starter tungsten heater was planned to be removed after the beginning of the radial melting. The sustained heating of the corium loading should provide a downward motion of the melting front. The thermocouples located in the peripheral area would indicate rapid increase of temperature. As the heating efficiency increased gradually with the melt pool propagation, it was anticipated that the input power would be reduced during the third phase to maintain constant melting front velocity.

Table 1 lists main events occurred during the test. The first phase was completed at the 4200th second (the pyrometer indication was about 2250°C). The rapid increase of the power input after the time point of 4200 s was associated with the input power transfer from the tungsten to the corium loading periphery when the heating efficiency increased significantly.
Table 1. Events during the test

<table>
<thead>
<tr>
<th>Events</th>
<th>Relative time, s</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start up of the data acquisition system</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Start up of the power input</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Temperature at the level 4 indicated the rapid increase</td>
<td>4100 – 4140</td>
<td>Melt front reached the peripheral area at the level 4 (380 mm)</td>
</tr>
<tr>
<td>Removal of the tungsten tube</td>
<td>4300</td>
<td>The pyrometer indicated the temperature about 2250°C</td>
</tr>
<tr>
<td>Temperature at the level 3 indicated rapid increase</td>
<td>4710 – 4950</td>
<td>Melt front reached peripheral area at the level 3 (320 mm)</td>
</tr>
<tr>
<td>Temperature at the level 2 indicated rapid increase</td>
<td>5910 – 6148</td>
<td>Melt front reached peripheral area at the level 2 (220 mm)</td>
</tr>
<tr>
<td>Shut down of the power input into the upper section</td>
<td>6273</td>
<td>Steel temperature reached the value of 1200°C</td>
</tr>
<tr>
<td>Temperature at the level 1 indicated rapid increase</td>
<td>7500 – 7920</td>
<td>Melt front reached peripheral area at the level 1 (130 mm)</td>
</tr>
<tr>
<td>Power input into steel in the upper section was resumed at</td>
<td>7512</td>
<td>Heating of steel up to temperatures close to the melting point</td>
</tr>
<tr>
<td>the level of 25 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of steel rapid heating in the upper section (power</td>
<td>8174</td>
<td>Steel thermocouples indicated the temperature higher than 1500°C. Steel melt introduction into</td>
</tr>
<tr>
<td>input ~ 140 kW)</td>
<td></td>
<td>the lower section.</td>
</tr>
<tr>
<td>The upper induction heating switching off</td>
<td>8403</td>
<td></td>
</tr>
<tr>
<td>Maintenance of the quasi-steady-state condition.</td>
<td>8400 - 9670</td>
<td>Variation of the power input to sustain steady-state temperature conditions</td>
</tr>
<tr>
<td>Power shut down</td>
<td>9670</td>
<td>Rapid temperature increase at the location of the bottom thermocouples</td>
</tr>
</tbody>
</table>

Figure 2. Temperature measured by peripheral thermocouples at different levels

![Temperature measured by peripheral thermocouples at different levels](image)

The tungsten starter heater was removed approximately at the 4300th second. Before this moment, thermocouples at the level 4 (380 mm from the bottom) indicated the rapid temperature increase that was interpreted as the melt approached the cold crucible walls. At the same time, heat removal by cooling water increased and exceeded the value of about 100 kW. Later, the power input into the system was
adjusted maintaining heat removal through the cooling system approximately at this level to keep integrity of the facility.

Figure 2 demonstrates the melt front movement from the top to the bottom with the thermocouple data at five different layers. The average melting front rate in the time interval between 4000 and 6000 seconds was about 0.08 mm/s, later it was about 0.05 mm/s.

Mathematical model

Specially developed computer code for simulation heat and mass transfer in the facility. The basic code for simulation was CONV 2D code [7], however some additional models were added. First, to define internal heat generation special model was developed. Second model for mass transfer between different phases was introduced in the code for simulation of interactions between corium and steel.

Initial heating of corium mixture was performed by the tungsten cylinder, which was heated by the high frequency up to the corium melting point. For simulation, the model developed for axially symmetrical cases was used.

For simulation of interaction between corium and steel the model was supplemented by the diffusion equation which describes transport of uranium and zirconium mixture in the steel.

Thus, because of the problem includes magnetic hydrodynamics, except of Navier-Stokes equation, Maxwell equations were used.

Maxwell equations

For the considered problem the Maxwell equations in the cylindrical coordinate system are as follows:

\[
\begin{align*}
\text{rot } E &= -\frac{\partial B}{\partial t} \\
\text{rot } H &= j + \frac{\partial D}{\partial t} \\
\text{div } D &= \rho \\
\text{div } B &= 0 \\
D &= \varepsilon_0 \varepsilon E, \quad B = \mu_0 \mu_p H
\end{align*}
\]

Where \(E\) and \(H\) - are the vectors for electric and magnetic fields correspondingly; \(D\) - electric induction; \(\varepsilon\) - is the relative dielectric permeability of the media; \(B\) - magnetic induction; \(\mu_p\) - the relative magnetic permeability of the media; \(\varepsilon_0 = \frac{10^{-7}}{4\pi c^2} K a^2 \cdot H^{-1} \cdot M^{-2} = 8.854187818 \cdot 10^{-12} \cdot A^2 \cdot \Phi^{-1} \cdot M^{-3} \cdot (\Phi \cdot M^{-1})\) - dielectric permeability of vacuum; \(\mu_0 = 4\pi \cdot 10^{-7} \cdot \kappa \cdot m \cdot c^{-2} \cdot (\Gamma \cdot M^{-1})\) - magnetic permeability of vacuum; \(\rho\) - electric charge density; \(j\) - density of electric current.

The current density and electric field strength are proportional, and \(\sigma\) is the conductivity \(j = \sigma E\).

Simplification of equations can be made if time derivative of D vector is neglected. In this case the system of equations can be written in the form:
rot $E = -\frac{\partial \mu_0 \mu_p H}{\partial t}$

rot $H = j$

\(\text{div}(\varepsilon_0 \varepsilon E) = 0\)

\(\text{div}(\mu_0 \mu_p H) = 0\)

If we assume that magnetic field can be presented in the form

$$\vec{H} = \{0,0,H(r,t)\}, \quad H = H_0 e^{i\omega t},$$

where $H_0$ - is the amplitude of oscillations slightly changed in time then

$$\text{rot}\vec{H} = -\frac{\partial H_0}{\partial r} e^{i\omega t} e^\phi,$$

$$\vec{E} = \frac{J}{\sigma} = \frac{\text{rot}\vec{H}}{\sigma}$$

and from equations (2) one can get

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial H_0}{\partial r} \right) = \frac{\partial (\mu_0 \mu_p H_0)}{\partial t} + i \omega \mu_0 \mu_p H_0$$

(3)

In (3) we can take into account that magnetic field strength can be represented as a sum of real and imaginary parts namely $H_0 = H_1 + iH_2$. Thus for two components of magnetic field the system of equation can be written in the form:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial H_1}{\partial r} \right) = -\omega \mu_0 \mu_p H_2 + \frac{\partial \mu_0 \mu_p H_1}{\partial t},$$

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial H_2}{\partial r} \right) = \omega \mu_0 \mu_p H_1 + \frac{\partial \mu_0 \mu_p H_2}{\partial t}$$

(4)

Equations are supplemented by boundary conditions at the outer boundary $H_1 = H_0$ and $H_2 = 0$.

In the case of RCW facility corium is not uniform and the problem is two dimensional. In this case the problem can be written for the scalar equation for vector potential $A$, which has only one azimuthal component. The equation can be obtained from the equation for magnetic field

$$\frac{\partial H}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial H}{\partial r} \right)$$

by the substitution $A = \text{rot}H$:

$$\frac{\partial A}{\partial t} = \frac{1}{\sigma} (\text{rot rot}A) = \frac{1}{\sigma} \Delta^* A.$$

In the cylindrical system of coordinates the equation for $A$ has the form:

$$\frac{\partial A}{\partial t} = \frac{1}{\sigma} \Delta^* A = \frac{1}{\sigma} \left( \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial (Ar)}{\partial r} \right) + \frac{\partial^2 A}{\partial z^2} \right)$$

(5)
For the problem with periodic conditions one can write the equations for real and imaginary parts $A_1$ and $A_2$ in the form:

\[
\frac{\partial A_1}{\partial t} = \frac{1}{\sigma} \Delta^* A_1 - \omega A_2, \\
\frac{\partial A_2}{\partial t} = \frac{1}{\sigma} \Delta^* A_2 + \omega A_1
\]  

(6)

If the load of the inductor is changed because of the change of corium conductivity the current and voltage are changed. These changes are determined by the scheme of power supply. If the voltage is sustained at the certain level then boundary value of the magnetic field is determined by the expression:

\[ V = V_c N, \]

where $V_c$ is the voltage along one turn, $N$ is the number of turns in one section.

In turn the voltage is calculated as

\[ V_c = \sqrt{V_1^2 + V_2^2}, \]

where $V_1 = \omega \mu_0 \int H_1 dS$, $V_2 = \omega \mu_0 \int H_2 dS$,  

(7)

at

\[ \mu_0 = 4\pi \times 10^{-7}, \quad \omega = 4.5 \times 10^4, \quad N = 9, \quad \omega \mu_0 N = 0.5. \]

**Diffusion of uranium and zirconium into steel**

For simulation of diffusivity of uranium and zirconium in the steel the following equation was used:

\[ \frac{\partial C}{\partial t} + \nu \text{grad} C = \text{div}(\kappa_D \text{grad} C), \]  

(8)

with the boundary conditions  

\[ \frac{\partial C}{\partial n} = 0. \]

In (8) $C$ is the concentration of uranium in the corium and steel, $\kappa_D$ is the diffusivity coefficient which has the value of $\kappa_D \approx 10^{-8} \div 10^{-7}$. At the initial time moment $C = 0$ - in the steel and $C = 1$ in the corium.

Relative density of steel depending upon uranium and zirconium content in the steel is presented in Figure 3. Although this dependence was obtained for room temperature the same relative dependence was used for liquid phase.
Navier Stokes equations

For modeling of incompressible flows the Navier – Stokes equations are used in the Bussinesque approximation for the buoyancy term in the natural variables together with the temperature equation:

\[
\frac{\partial \mathbf{v}}{\partial t} + C(v)\mathbf{v} - \nabla(v \nabla \mathbf{v}) + \nabla \mathbf{p} = f, \quad \nabla \cdot \mathbf{v} = 0, \tag{9}
\]

\[
\frac{\partial h}{\partial t} + \bar{C}(v)h - \nabla(k \nabla T) = q, \quad h = \int_0^\tau \mathcal{C}(\xi) d\xi, \tag{10}
\]

The latent heat of melting \( L \) is included through the effective heat capacity \( c^{\text{eff}} \) defined as follows:

\[
c^{\text{eff}} = \begin{cases} 
    c + L \delta(T - T^*) & \text{— pure materials,} \\
    c + L \frac{d\Phi}{dT} & \text{— alloys and mixtures.}
\end{cases}
\]

The following notation are used: \( p \) is the pressure, normalized on the density; \( L \) is the latent heat of melting; \( \delta \) — delta function; \( T^* \) — melting temperature; \( \Phi \) — solid fraction; \( C \) и \( \bar{C} \) — operators for convective terms.

Heat source \( q \) in equation (10) is the Joule heating by the current

\[
q = \frac{|j|^2}{2\sigma} = \frac{1}{2\sigma} \left( \frac{\partial H_j}{\partial r} \right)^2 + \left( \frac{\partial H_j}{\partial r} \right)^2.
\]

In equation (9) \( f \) defines the buoyancy forces due to temperature and uranium concentration gradients.
Results of analysis

In accordance with the test procedure simulation of the experiment has been conducted in three phases:

1. Preliminary heating of corium by the tungsten cylinder;
2. Heating of corium by electromagnetic radiation;
3. Steel addition and diffusion of uranium to steel.

The first phase is characterized by the heating of tungsten cylinder and spreading of the heated area in radial direction. The duration of first phase was about 4300 s. At approximately 4000 s the heat generated in the facility was moved from the tungsten to corium and at 4300 s boundary skin layer was formed as it is shown in Figure 4. Temperature at the end of this phase reached the corium melting point.

Figure 4. Power Generated in the Corium (left column) and Isotherms between 1000 and 2500 K for Two Time Instants – 4000 and 4300 Seconds
The second phase is characterized by the gradual spreading of molten corium in axial direction. The duration of this phase was between 4300 and 8200 s. Heat is generated in a thin skin layer near cold crucible boundary. Power generated in the corium and isotherms for two time instants 5618 and 8173 s are shown in Figure 5. One can also see that near the heated end the spike of heat generation is observed. This spike which led to the increase in temperature was measured by thermocouples as it is shown in Figure 6. This behaviour is a good qualitative agreement with the measurements presented in Figure 2. The flow of molten corium during this phase is characterized by the complex flow formed from one side by the down flow near the cooled boundary and upward flow due to heating of skin layer as it is shown in Figure 7. Temperature during this phase is nearly uniform.

The third phase was between 8173 s and 9260 s up to the shut down of the test. In was assumed that before steel addition there was a stable crust at the top surface of corium. After steel addition it was assumed that crust was not broken, thus, just after steel delivery it formed a layer atop of corium. Screening of radiation from the upper surface led to the heating of corium region just below the steel corium interface. This in turn led to the softening of crust and loss its mechanical integrity allowing steel to interact with corium. Diffusivity of uranium in the steel led to the increase of metal density. When density of metal layer became larger than oxide density, the Rayleigh – Taylor instability was developed and caused movement of metal downward. This process is illustrated in Figure 8.
From these pictures one can see that metal fragments move downward and after reach of unmelted corium part forms jets and metal fragments in corium. Note that under certain condition not all metal interacted with corium, so at the top of the facility one may observe thin metal layer which remained lighter than corium. This corresponds quantitatively to the observations made after facility disassembly.

In the calculations also another scenario was considered. It was assumed that there was no crust at the top, therefore metal can penetrate into corium. During relocation melt may fragment. Interaction of fragments with corium will also lead to the uranium extraction from corium mixture. The interaction will be faster for small fragments. Large fragments will be collected at the top, while small droplets will sink. One can see that both scenario may finally lead to one picture, with some change of sequence of events.
Figure 8. Volumetric Part, Uranium Content and Temperature Distribution at 9232 s (left) and 9238 s (right)
Discussion

In spite of the fact that before the test there were significant uncertainties in the physical properties of the corium at low temperatures, the analysis indicated a good qualitative and even quantitative agreement between the test results and predictions.

Comparing of curves presented in Figure 6 with experimental data (Figure 2) one should take into account that calculated temperature plots correspond to the initial location of thermocouples at the interface surface between thermal insulation powder (8 mm thick) and corium loading. After the facility was disassembled, it was found out that the length of W-Re thermocouples became shorter due to the melting of their hot ends after the corium melt front passed thermocouple positions. The thermocouples restored their qualitative indications at new locations (~effective distance was 2 - 3 mm from cold crucible pipes) after the end of the shroud melting process. The shift of measuring points closer to the cold crucible determined the deviation of calculated and measured values in the time interval between 5400 and 9000 seconds.

![Figure 9. The Macrosection of the Ingot Central Cut](image)

In Figure 9 the cross section of the ingot is presented. Metal phase was found at different locations: at the bottom of the pool (2), at the pool surface (7) and in the middle part (4). Qualitative explanation of the observed picture was discussed earlier.

Thus, model developed for solving conjugate problem including convection in the molten pool, heat generation in tungsten tube or in heated corium, melting of corium and diffusion of corium components to metal layer allowed to obtain qualitative explanation of the interaction pattern in the large scale test RCW.
References


